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Parton–Hadron Duality in *B* Meson Decays

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Abstract

We summarize the current view on Parton-Hadron duality as it applies to B meson decays. It is emphasized that an OPE treatment is essential for properly formulating duality and its limitations. Duality violations are unlikely to become the limiting factor in describing semileptonic B width vis-a-vie higher order corrections. The consistent extraction of the b quark mass from B production and decays provides a striking example of the theoretical control achieved.

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1 Introduction

Parton-hadron duality [2] – or duality for short – is one of the central concepts in contemporary particle physics. It is invoked to connect quantities evaluated on the quark-gluon level to the (observable) world of hadrons. It is used all the time, more often than not without explicit reference to it. A striking example of the confidence the HEP community has in the asymptotic validity of duality was provided by the discussion of the width $\Gamma(Z^0 \to H_b H_b' X)$. There was about a 2% difference in the predicted and measured decay width, which lead to lively debates on its significance vis-a-vis the *experimental* error. No concern was expressed about the fact that the Z^0 width was calculated on the quark-gluon level, yet measured for hadrons. Likewise the strong coupling $\alpha_S(M_Z)$ is routinely extracted from the perturbatively computed hadronic Z^0 width with a stated theoretical uncertainty of 0.003 with translates into a theoretical error in $\Gamma_{had}(Z^0)$ of about 0.1%.

There are, however, several different versions and implementations of the concept of duality. The problem with invoking duality implicitly is that it is very often unclear which version is used. In B physics – in particular when determining $|V(cb)|$ and $|V(ub)|$ – the measurements have become so precise that theory can no longer hide behind experimental errors. To estimate theoretical uncertainties in a meaningful way one has to give clear meaning to the concept of duality; only then can one analyze its limitations.

In response to the demands of B physics a considerable literature has been created on duality over the last few years, which we want to summarize. We will emphasize and illustrate the underlying principles; technical details can be found in the references we list.

Duality for processes involving time-like momenta was first addressed theoretically in the late '70's in references [1] and [2]. We sketch here the argument of Poggio, Quinn and Weinberg since it contains several of the relevant elements in a nutshell. The cross section for $e^+e^- \to$ *hadrons* can be expressed through an operator product expansion (OPE) of two hadronic currents. One might be tempted to think that by invoking QCD's asymptotic freedom one can compute $\sigma(e^+e^- \to \text{hadrons})$ for large c.m. energies $s \gg \Lambda_{QCD}$ in terms of quarks (and gluons) since it is shaped by short distance dynamics. However production thresholds like for charm induce singularities that vitiate such a straightforward computation. This complication can be handled in the following way. Consider the correlator of two electromagnetic currents:

$$T_{\mu\nu}(q^2) = \int d^4x\, e^{iqx} \langle 0|T\left(J_\mu(x)J_\nu(0)\right)|0\rangle = (q_\mu q_\nu - g_{\mu\nu}q^2)\Pi(q^2) \tag{1}$$

where $\Pi(q^2)$ can be written in terms of a spectral function $\rho(s)$ using an unsubtracted dispersion relation:

$$\Pi(q^2) = \int \frac{ds}{2\pi} \frac{\rho(s)}{q^2 - s + i\epsilon} \tag{2}$$

It is well known that, to leading order in α_{em}, $\rho(s)$ is related to the total cross section for $e^+e^- \to$ hadrons

$$\sigma(s) = \frac{4\pi\alpha_{em}}{s}\rho(s) \tag{3}$$

Relying on QCD's asymptotic freedom one computes the correlator (1) in terms of quarks and gluons for s in the deep Euclidean domain $|s| \gg \Lambda_{QCD}$; s is chosen Euclidean so

[2] This name might be more appropriate than the more frequently used *quark*-hadron duality since gluonic effects have to be included as well into the theoretical expressions.

that one avoids a proximity to singularities induced by hadronic thresholds like for charm production etc. From the spectral function ρ calculated in the Euclidean regime one can infer the cross section for physical, namely Minkowskian values of s. However, one cannot obtain it as a point-for-point function of s, only averaged – or 'smeared' – over an energy interval, which can be written symbolically as follows:

$$\rho(s_{Euclid}) \Rightarrow \int_{s_0}^{s_0+\Delta s} ds\sigma(e^+e^- \to hadrons) \tag{4}$$

This feature is immediately obvious: for the smooth s dependence ρ has to be compared to the measured cross section $e^+e^- \to$ hadrons as a function of s, which has pronounced structures, in particular close to thresholds for $c\bar{c}$- and $b\bar{b}$-production.

This simple illustration already points to the salient elements and features of duality and its limitations:

- An OPE description in terms of quark and gluon degrees of freedom for the observable under study is required.
- This OPE has to be constructed in the Euclidean domain.
- Its results are analytically continued to the Minkowskian domain with the help of a dispersion relation.
- This extrapolation implies some loss of information; i.e. in the notation given above

  $$\langle T_{\mu\nu}^{hadronic} \rangle_w \simeq \langle T_{\mu\nu}^{partonic} \rangle_w \tag{5}$$

  where $\langle ... \rangle_w$ denotes the smearing which is an average using a smooth weigth function $w(s)$; it generalizes the simplistic use of a fixed energy interval:

  $$\langle ... \rangle_w = \int ds \, ... \, w(s) \tag{6}$$

- Some contributions that are quite insignificant in the Euclidean regime and therefore cannot be captured through the OPE can become relevant after the analytical continuation to the Minkowskian domain, as explained later on. For that reason we have used the approximate rather than the equality sign in Eq.(5).
- One can make few universal statements on the numerical validity of duality. How much and what kind of smearing is required depends on the specifics of the reaction under study.

The last item needs expanding right away. The degree to which $\langle T_{\mu\nu}^{partonic} \rangle_w$ can be trusted as a theoretical description of the observable $\langle T_{\mu\nu}^{hadronic} \rangle_w$ depends on the weight function, in particular its width. It can be broad compared to the structures that may appear in the hadronic spectral function, or it could be quite narrow, as an extreme case even $w(s) \sim \delta(s - s_0)$. It has become popular to refer to the first and second scenarios as *global* and *local* duality, respectively. Other authors use different names, and one can argue that this nomenclature is actually misleading. Below we will describe these items in more detail without attempting to impose ex cathedra a uniform nomenclature ourselves.

Irrespective of names, a fundamental distinction concerning duality is often drawn between semileptonic and nonleptonic widths. Since the former neccessarily involves smearing with a smooth weight function due to the integration over neutrino momenta, it is often argued that predictions for the former are fundamentally more trustworthy than for the latter. However, as we shall see, such a categorical distinction is overstated and artificial; also it is not needed for the discussion in the following chapters. Of much more relevance is the differentiation between distributions and fully integrated rates.

No real progress beyond the more qualitative arguments of Refs. [1] and [2] occurred for many years. For as long as one has very limited control over nonperturbative effects, there is little meaningful that can be said about duality violations. Yet this has changed for heavy flavour physics with the development of heavy quark expansions, since within this OPE framework we can assess nonperturbative effects as well as duality violations.

The remainder of this note will be organized as follows: In the next section we shall give a more precise definition of what is meant with "Parton Hadron Duality", which then allows us a discussion of possible violations of duality in section 3. Based on this we give hints on how to check the concept of duality in section 4, before presenting conclusions.

2 What is Parton–Hadron Duality?

In order to discuss possible violations of duality we have to give first a more precise definition of this notion, which requires the introduction of some theoretical tools. We follow closely the arguments given in the extensive reviews of Ref. [3] and [4][3]. The central ingredient into this definition is the method of the Wilsonian *Operator Product Expansion* (OPE) frequently used in field theory to perform a separation of scales. In practical terms this means that we can write

$$\int d^4x\, e^{iqx} \langle A|T\left(J^\mu(x)J^\nu(0)\right)|A\rangle \simeq \sum_n \left(\frac{1}{Q^2}\right)^n c_n^{\mu\nu}(Q^2;\lambda)\langle A|\mathcal{O}_n|A\rangle_\lambda \tag{7}$$

for $Q^2 = -q^2 \to \infty$. The following notation has been used: $|A\rangle$ denotes a state that could be the vacuum – as for $e^+e^- \to hadrons$ considered above – or a B meson when describing semileptonic beauty decays. J^μ denote electromagnetic and weak current operators for the former and the latter processes, respectively; for other decays like nonleptonic or radiative ones one employs different $\Delta B = 1$ operators; the $\mathcal{O}_n$ are local operators of increasing dimension. The operator of lowest dimension yields the leading contribution. In e^+e^- annihilation it is the unit operator $\mathcal{O}_0 = 1$, for B decays $\mathcal{O}_0 = \bar{b}b$. They produce (among other things) the naive partonic results. Yet the OPE allows us to systematically improve the naive partonic result. The coefficients $c_n^{\mu\nu}$ contain the contributions from short distance dynamics calculated perturbatively based on QCD's asymptotic freedom. Following Wilson's prescription a mass scale λ has been introduced to separate long and short distance dynamics; both the coefficients and the matrix elements depend on it, their product of course not.

The perturbative expansion takes the form

$$c_n^{\mu\nu} = \sum_i \left(\frac{\alpha_S(Q^2)}{\pi}\right)^i a_{n,i}^{\mu\nu} \tag{8}$$

[3]It can be noted that even the authors of Ref.[3] and [4] – although very close in the substance as well as the spirit of their discussion – do not use exactly the same terminology concerning different aspects of duality.

and is performed in terms of quarks and gluons. The expectation values for the local operators provide the gateways through which nonperturbative dynamics enters.

The crucial point is that the OPE result is obtained in the Euclidean domain and has to be continued analytically into the Minkowskian regime relating the OPE result to observable hadronic quantities. As long as QCD is the theory of the strong interactions, it does not exhibit unphysical singularities in the complex Q^2 plane, and the analytical continuation will not induce additional contributions. To conclude: *duality between* $\langle T_{\mu\nu}^{hadronic}\rangle_w$ *and* $\langle T_{\mu\nu}^{partonic}\rangle_w$ *arises due to the existence of an OPE that is continued analytically.* It is just a restatement of QCD's basic tenet as the theory of the strong interactions that hadronic observables can be expressed in terms of quark-gluon degrees of freedom *provided* all possible sources of corrections to the simple parton picture are properly accounted for. It is thus misleading to refer to duality as an additional assumption.

Up to this point our discussion was quite generic. To specify it for semileptonic B decays one chooses the current J_μ to be the weak charged current driven by $b \to c$ or $b \to u$. The expansion parameter for inclusive semileptonic decays is given by the energy release $\sim 1/(m_b - m_c)$ $[1/m_b]$ for $b \to c$ $[b \to u]$. For the exclusive mode $B \to l\nu D^*$ it is $1/m_b$ and $1/m_c$ with the latter yielding the numerically leading contributions.

3 Duality Violations and Analytic Continuation

One of the main applications of the heavy quark expansion is the reliable extraction of $|V(cb)|$ and $|V(ub)|$. One wants to be able to arrive at a meaningful estimate of the theoretical uncertainty in the values obtained. There are three obvious sources of theoretical errors:

1. unknown terms of higher order in α_S;
2. unknown terms of higher order in $1/m_Q$;
3. uncertainties in the input parameters α_S, m_Q and the expectation values.

Duality violations constitute uncertainties *over and above* these; i.e. they represent contributions not accounted for due to

- truncating these expansions at finite order and
- limitations in the algorithm employed.

These two effects are not unrelated. The first one means that the OPE in practice is insensitive to contributions of the type $e^{-m_Q/\mu}$ with μ denoting some hadronic scale; the second one reflects the fact that under an analytic continuation the term $e^{-m_Q/\mu}$, which is quite irrelevant for $Q = b$ – though not neccessarily for $Q = c$! – turns into an oscillating rather than suppressed term $\sin(m_Q/\mu)$.

Of course we do not have (yet) a full theory for duality and its violations. Yet we know that without an OPE the question of duality is ill-posed. Furthermore in the last few years we have moved beyond the stage, where we could merely point to folklore. This progress has come about for the following reasons:

- We have refined our understanding of the physical origins of duality violations as due to

- hadronic thresholds;
- so-called 'distant cuts';
- the suspect validity of $1/m_c$ expansions.

- We understand the mathematical portals through which duality violations can enter, namely that the innocuous Euclidean quantity $e^{-m_Q/\mu}$ transmogrifies itself into the much more virulent Minkowskian quantity $\sin(m_Q/\mu)$ under analytical continuation.

- The quantity $e^{-m_Q/\mu}$ is actually innocuous for beauty, yet not necessarily for charm quarks. The 'Euclidean' quantity $F_{D^*}(0)$ – the formfactor for $B \to l\nu D^*$ at zero recoil –, which is given by an expansion in $1/m_c$, could be vulnerable to such a duality violation. However, the heavy mass expansion for exclusive quantities such as $F_{D^*}(0)$ is not directly given by an OPE, thus this argument may not apply in this case.

- We have come up with an increasing array of field-theoretical toy models, chief among them the 't Hooft model, which is QCD in 1+1 dimensions in the limit of $N_C \to \infty$. It is solvable and thus allows an unequivocal comparison of the OPE result with the exact solution.

- For the analysis of $b \to c$ transitions we also have the small-velocity expansion as a powerful tool.

We will not go into any details here, since they can be found in the literature [4]. The models do exhibit duality violations, but only highly suppressed ones conforming to general expectations. There had been claims of sizeable duality violations in the previous literature; those have been analyzed carefully in Ref.[4], where their flaws are pointed out explicitly.

Based on general expectations as well as on analyzing the models one finds that indeed duality violations are described by highly power suppressed 'oscillating' terms of the form

$$T(m_Q) \sim \left(\frac{1}{m_Q}\right)^k \sin(m_Q \lambda) \tag{9}$$

for some integer power k. More generally one can state:

- The primary criterion for addressing duality violation is the existence of an OPE for the particular observable.

- Duality will not be exact at finite masses. It represents an approximation the accuracy of which will increase with the energy scales in a way that depends on the process in question.

- Limitations to duality can enter only in the form of an oscillating function of energy or m_Q (or have to be exponentially suppressed). Duality violations *cannot be blamed for a systematic excess or deficit in the decay rates.* For example, no duality violation can convert m_Q into M_{H_Q} in the full width parametrically, only for discrete values of m_Q.

- The OPE equally applies to semileptonic as well as nonleptonic decay rates. Likewise both widths are subject to duality violations. The difference here is quantitative rather than qualitative; at finite heavy quark masses corrections are generally expected to be larger in the nonleptonic widths. In particular, duality violations there can be boosted by the accidental nearby presence of a narrow hadronic resonance. Similar effects could arise in semileptonic rates, but are expected to be highly suppressed there.

- It is not necessary to have a proliferation of decay channels to reach the onset of duality, either approximate or asymptotic. Instructive examples are provided by the so-called small-velocity kinematics in semileptonic decays and by nonleptonic rates in the 't Hooft model.

Putting everything together it has been estimated with considerable confidence – at least by the authors of Ref.[4] – that *duality violations in the integrated semileptonic width of B mesons cannot exceed the fraction of a percent level.* As such we do not envision it to ever become the limiting factor in extracting $|V(cb)|$ and $|V(ub)|$ since the uncertainties in the expression for the semileptonic width due to fixed higher order contributions will remain larger than this level. The oscillatory nature of duality violating contributions is a main ingredient in this conclusion. It also shows that duality violations could become quite sizeable if an only partially integrated width – let alone a distribution – is considered. Generally, for distributions the expansion parameter is not the heavy mass, rather it is a quantity such as $1/[m_Q(1-x)]$ where x is e.g. the rescaled charged lepton energy of a semileptonic decay. From equation (9) one would expect that contributions the form $\sin(m_Q[1-x])/[m_Q(1-x)]^k$ appear in differential distributions.

4 How can we check the validity of Parton–Hadron Duality?

If in the future we were to find a discrepancy between the measured and predicted values for, say, a CP asymmetry in B decays, we had to check very diligently all ingredients upon which the prediction was based, in particular the values for $V(cb)$ and $V(ub)$, before we could make a credible claim to have uncovered New Physics. This means one needs a measure for potential duality violations that is not based purely on theoretical arguments.

Most theoretical uncertainties are systematical rather than statistical. As it is the case for experimental systematics the most convincing way to establish control over them is to determine the same quantity in independent ways and analyze their consistency. The heavy quark expansions lend themselves naturally to such an approach since it is their hallmark that they allow the description of numerous decay rates in terms of a handful of basic parameters, namely quark masses and hadronic expectation values. Again the situation is very similar as for the perturbative series: once the coupling constant is determined (e.g. $\alpha_S(M_Z)$) from a measurement, one may use this as an input to all other perturbative calculations, thereby predicting other measurements. If a prediction obtained in this way fails, one would conclude that higher order effects have to be unusually large or that there is another deeper reason why a perturbative treatment does not apply.

Such independent determinations of the same quantity of course probe the overall theoretical control that we have established. By themselves they do not tell us whether a failure found is due to unusally large higher order contributions or to a breakdown in duality.

The fact that both the inclusive and exclusive methods for extracting $|V(cb)|$ yield consistent values – and that the theoretical corrections one had to apply are both nontrivial and essential for the agreement – is such a test. We want to point to two other such tests that have become available, namely concerning the b quark mass and its kinetic energy expectation value.

4.1 b quark mass

The b quark mass has been extracted from beauty production at threshold in e^+e^- annihilation by several authors [9]. Their findings can be stated in terms of two definitions of quark masses:

(i) The 'kinetic mass' is defined by

$$\frac{dm_Q^{kin}(\mu)}{d\mu} = -\frac{16}{9}\frac{\alpha_S(\mu)}{\pi} - \frac{4}{3}\frac{\alpha_S(\mu)}{\pi}\frac{\mu}{m_Q} + \mathcal{O}\left(\alpha_S^2, \alpha_S \cdot \frac{\mu^2}{m_Q^2}\right) , \tag{10}$$

normalized at 1 GeV; it is well-defined in full QCD and does not suffer from a renormalon ambiguity; equivalently one can use

$$\bar{\Lambda}(\mu) \equiv \lim_{m_Q\to\infty} \left[M(H_Q) - m_Q^{kin}(\mu)\right] . \tag{11}$$

where $M(H_Q)$ is the mass of the 0^- ground state.

(ii) The pole or HQET mass which is a very popular choice, although it is not well-defined in full QCD since it suffers from the renormalon ambiguity. If appropriate care and caution are applied one can still use it in calculation; as a rule of thumb one has for its relatioship to the kinetic mass:

$$\bar{\Lambda}_{\rm HQET} = \bar{\Lambda}(1 \text{ GeV}) - 0.255 \text{ GeV} \tag{12}$$

where the parameter $\bar{\Lambda}$ is defined in the same way as in (11):

$$\bar{\Lambda}^{HQET} \equiv \lim_{m_Q\to\infty}[M(H_Q) - m_Q^{pole}] \tag{13}$$

The results are completely consistent within the stated uncertainties of 1-2 % and can be summarized as follows:

$$m_b^{kin}(1 \text{ GeV})|_{e^+e^-\to\bar{b}b} = 4.57 \pm 0.06 \text{ GeV} \leftrightarrow \bar{\Lambda}(1\,\text{GeV}) = 0.71 \pm 0.06 \text{ GeV} \tag{14}$$

or

$$m_b^{pole} = 4.82 \pm 0.06 \text{ GeV} \leftrightarrow \bar{\Lambda}^{HQET} = 0.45 \pm 0.06 \text{ GeV} \tag{15}$$

The techniques employed in the analysis differ somewhat from author to author; the full agreement in their findings is thus quite re-assuring. One should keep in mind, though, that these determinations share their experimental input to a large degree. The value stated in Eq.(14) could thus be subject to some systematic shift from the true value. Arguments based on the small-velocity sum rules indeed suggest that $m_b^{kin}(1 \text{ GeV})$ could lie a bit above 4.6 GeV.

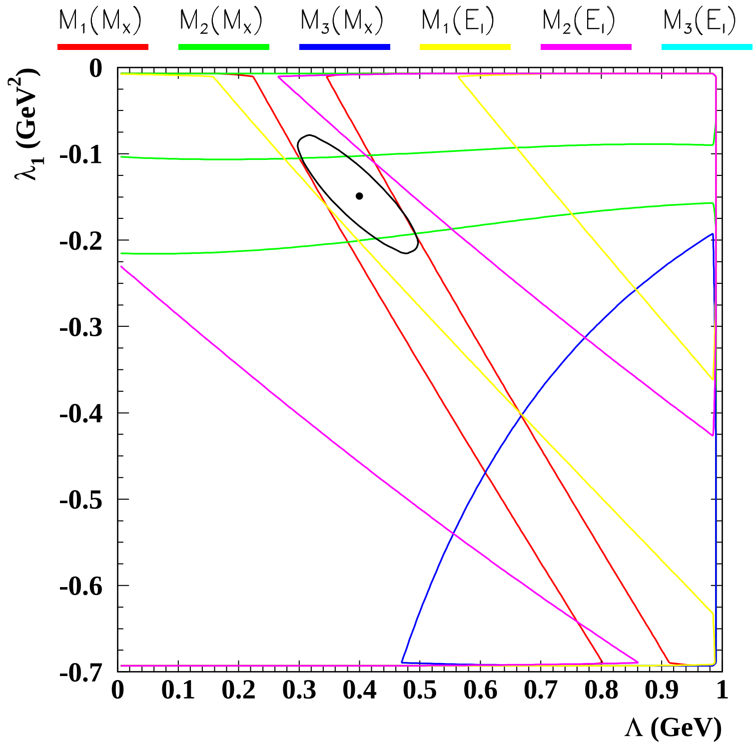

Figure 1: Contours in the $\bar{\Lambda}$-λ_1 plane, from the DELPHI measurement of the first and second moments [11]. The band defined by the almost flat curves in the upper part are from the second moment of the hadronic invariant mass, the steepest straight line is from the first moment of the hadronic invariant mass. The remaining curves are from the moments of the lepton energy, the steeper being from the first moment. The curve in the lower right is from the third moment of the hadronic in variant mass.

The b quark mass also affects the shape of lepton energy and hadronic mass spectra in semileptonic (and photon spectra in radiative) B decays. Its value can therefore be obtained from the measured lepton energy and hadronic mass moments, which encode the shape of these spectra. The DELPHI and CLEO collaborations have presented data as shown in the Figures 1 and 2. Again it is pleasing to see that the different moments indeed yield completely consistent values although this is not truly surprising since they are highly correlated. DELPHI finds

$$
\begin{aligned}
m_b^{kin}(1\ \text{GeV})|_{mom} &= 4.59 \pm 0.08 \pm 0.01\ \text{GeV} && (16)\\
&\leftrightarrow\ \bar{\Lambda}(1\,\text{GeV}) = 0.69 \pm 0.08 \pm 0.01\ \text{GeV} \\
m_b^{pole}|_{mom} &= 4.88 \pm 0.10 \pm 0.02\ \text{GeV} && (17)\\
&\leftrightarrow\ \bar{\Lambda}^{HQET} = 0.40 \pm 0.10 \pm 0.02\ \text{GeV}
\end{aligned}
$$

It is again reassuring that their fit results are consistent with Eq.(14) CLEO measures truncated lepton energy moments and states their findings in terms of HQET parameters

$$
\begin{aligned}
m_b^{pole}|_{mom} &= 4.88 \pm 0.03 \pm 0.06 \pm 0.12\ \text{GeV} && (18)\\
&\leftrightarrow\ \bar{\Lambda}^{HQET} = 0.39 \pm 0.03 \pm 0.06 \pm 0.12\ \text{GeV}
\end{aligned}
$$

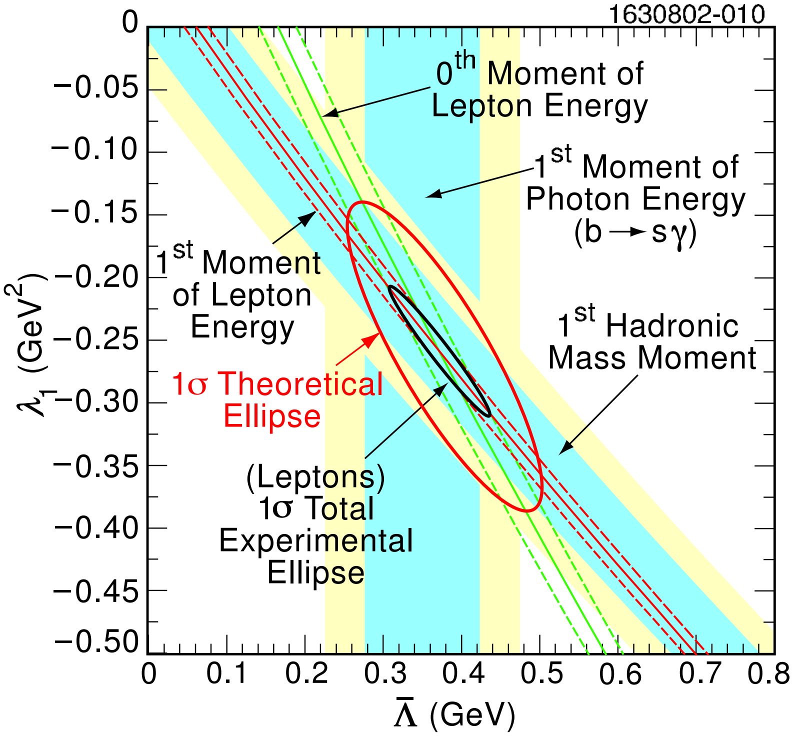

Figure 2: Contours in the $\bar{\Lambda}$-λ_1 plane, from the CLEO measurements of the moments [12].

The main news here is how well the values for m_b extracted from two sources agree that are quite different in their experimental as well as theoretical systematics, namely weak B decays and the electromagnetic production of beauty at threshold.

4.2 Average kinetic energy

A similarly pleasing picture emerges from determining the kinetic expectation value. Based on QCD sum rules and SV sum rules one had inferred for the infrared stable quantity $\mu_\pi^2(1\,\mathrm{GeV})$:

$$\mu_\pi^2(1\,\mathrm{GeV}) \simeq 0.45 \pm 0.1\ (\,\mathrm{GeV})^2\ . \tag{19}$$

Using the rule of thumb for the relation to the HQET parameter λ_1 [13]

$$-\lambda_1 \simeq \mu_\pi^2(1\,\mathrm{GeV}) - 0.18(\,\mathrm{GeV})^2 \tag{20}$$

this estimate translates into

$$-\lambda_1 \simeq 0.27 \pm 0.1(\,\mathrm{GeV})^2 \tag{21}$$

The aforementioned DELPHI and CLEO analyses also yield values for this quantity, namely

$$\mu_\pi^2(1\,\mathrm{GeV}) = 0.31 \pm 0.07 \pm 0.02\ (\,\mathrm{GeV})^2\ \ \mathrm{DELPHI} \tag{22}$$
$$-\lambda_1 = 0.15 \pm 0.07 \pm 0.03\ (\,\mathrm{GeV})^2\ \ \mathrm{DELPHI} \tag{23}$$
$$-\lambda_1 = 0.25 \pm 0.02 \pm 0.05 \pm 0.14\ (\,\mathrm{GeV})^2\ \ \mathrm{CLEO} \tag{24}$$

The fact that the parameters extracted in different way and form different observables yield consistent values for the quark mass and the kinetic energy parameter indicates that no anomalously large higher order corrections or unexpectedly sizeable duality violating contributions are present.

5 Conclusions

From all what we know currently from purely theretical considerations duality violations should be safely below one percent in the semileptonic branching ratio. This is likely to remain in the noise level of theoretical uncertainties due to terms of order $1/m_b^3$ and higher and of higher order perturbative contributions. Hence we do not see any need to assign some additional uncertainty to the extraction of V_{cb} from a possible duality violation in inclusive decays. This should not be seen as an ex cathedra statement. When more and more types of moments will be measured with more and more accuracy – even separately in the decays of B_d, B^- and B_s mesons –, additional constraints will be placed on the same set of heavy quark parameters. This will provide highly nontrivial tests of our theoretical control.

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